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Effect of Magnetic Flow and Convective Heat Transfer Enhancement using Hybrid Nanofluid: A Structured Review

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ABSTRACT

Convective heat transfer is vital in a variety of engineering applications, including thermal management systems, electronic refrigeration, and energy conversion devices. Improving the rate of heat transfer in these systems is of the utmost significance for increasing their efficiency. This review focuses on the single and combined effects of these parameters on improving heat transmission in such systems. The heat and mass transfer of nanofluid is greatly influenced by various factors, including the intrinsic features of the nanofluid, the process used for synthesising the nanofluid, the impact of magnetic force, the concentration and size of nanoparticles, and the Reynolds number (Re). Furthermore, it is important to note that the material characteristics, thermal properties, and performance of magnetic nanofluids are significantly influenced by slight variations in the magnetic force and magnetic field gradient. Multiple research projects have reached the agreement that the inclusion of a magnetic field within magnetic nanoparticles enhances the convective heat transfer capabilities of a nanofluid, resulting in an improvement ranging from around 13% to 75%. Moreover, several applications of hybrid nanofluids in thermal systems have been introduced.

Keywords:
Hybrid nanofluid; MHD flow; convective heat transfer enhancement

1. Introduction

The study of fluid behaviour and heat transfer in the presence of magnetic fields is the subject of the rapidly expanding scientific topic known as magnetic flow and heat transfer in hybrid nanofluid. A base fluid, magnetic nanoparticles, and non-magnetic nanoparticles are all combined to create the hybrid nanofluids [1]. The development of a magnetic nanofluid occurs through the addition of magnetic nanoparticles to a base fluid. This generated fluid is subject to the influence of an external magnetic field [2,3]. The magnetic field can lead the magnetic nanoparticles to align themselves, resulting in changes in the flow behaviour and heat transfer properties of the fluid. Due to its potential applications in a few industries, including energy engineering, electronic cooling, and biomedical engineering, the research of magnetic flow and heat transfer in hybrid nanofluids has

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attracted a lot of attention [4-6]. On magnetic flow and heat transmission in hybrid nanofluids, many investigations have been done.

Along with the requirement for environmentally friendly and renewable energy sources, another important objective is to maximise the efficiency of currently available energy systems. One of these systems, the heat exchanger, required extreme care [7-12].

Higher heat transfer capabilities for these systems can only be obtained by using active and passive strategies, even if improving heat transfer is one of the top priorities for many engineering applications where energy conservation and efficiency are crucial [13]. Researchers are experimenting with various combinations of passive, active, and hybrid ways to increase the convective heat transfer performance of thermal systems, as shown in Figure 1.

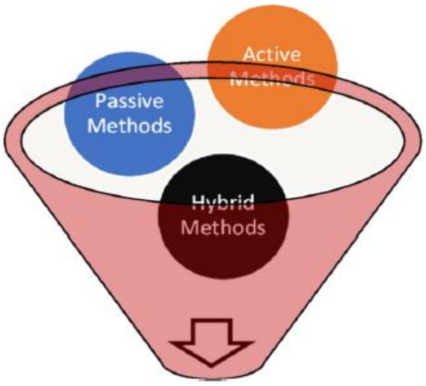

Fig. 1. Heat transfer enhancement methods [13]

Hu and Gao [14] and Gurdal *et al.,* [15] for instance, investigated how a magnetic field affected the convective heat transfer of magnetic fluid in a circular tube. They discovered that the magnetic field induces a flow motion of magnetic nanoparticles in the fluid, which improves heat transmission. Likewise, Li *et al.,* [16] investigated how a magnetic nanofluid flowed and transferred heat in a horizontal tube while being influenced by a transverse magnetic field. They discovered that a secondary flow that improves heat transfer is induced by the magnetic field. Hybrid nanofluids' thermal conductivity has also been thoroughly investigated. A survey of current developments in the thermal conductivity of hybrid nanofluids was done by Rashidi *et al.,* [17]. They claimed that mixing magnetic nanoparticles with non-magnetic nanoparticles improved the fluid's thermal conductivity. Also, they discovered that as the volume proportion of nanoparticles grows, the hybrid nanofluid's thermal conductivity rises. Investigations have also been done into how particle size and shape affect magnetic nanofluid flow behaviour and heat transmission. The impact of particle size and shape on the thermal conductivity of hybrid nanofluids, for instance, was investigated by Wang *et al.,* [18] in 2019. They discovered that as the particle size and aspect ratio of non-magnetic nanoparticles decrease, the hybrid nanofluid's thermal conductivity increases. In contrast, when the aspect ratio of magnetic nanoparticles increases, so does their thermal conductivity. It has also been investigated how magnetic nanofluid flow dynamics and heat transport are affected by the surface functionalization of nanoparticles. For instance, Chakraborty *et al.,* [19] studied how surface functionalization of nanoparticles affected magnetic nanofluid flow and heat transmission. They claimed that the inclusion of a surfactant that improves the dispersion of nanoparticles in the fluid increased the thermal conductivity of the magnetic nanofluid. The behaviour of magnetic nanofluids has been investigated using a variety of numerical and experimental techniques. For instance, Usman *et al.,* [20] investigated the flow and heat transfer of a magnetic nanofluid in a channel under the influence of a magnetic field using a numerical simulation. They noticed that the magnetic field causes magnetic nanoparticles to move in a flow, which improves heat transmission.

Figure 2 illustrates the numbers of papers relevant to nanofluids published over the past decade. Experimental research into nanofluids have intensively increased throughout the last 20 years. Currently, many researchers are focusing on a new type of nanofluid by dispersing more than two different particles into conventional heat transfer fluids, which are called hybrid nanofluids. In general, a hybrid nanofluid can achieve better dispersion stability than other nanofluids since each nanofluid can be employed with a lower concentration. In the context of employing a hybrid nanofluid, which involves the combination of many nanoparticles within a base fluid, it becomes imperative to assess the compatibility of each nanoparticle and its ability to interact with the working fluid in a thermal system. The investigation of dispersion stability in a hybrid nanofluid is crucial due to the variation in critical concentration required for each nanoparticle.

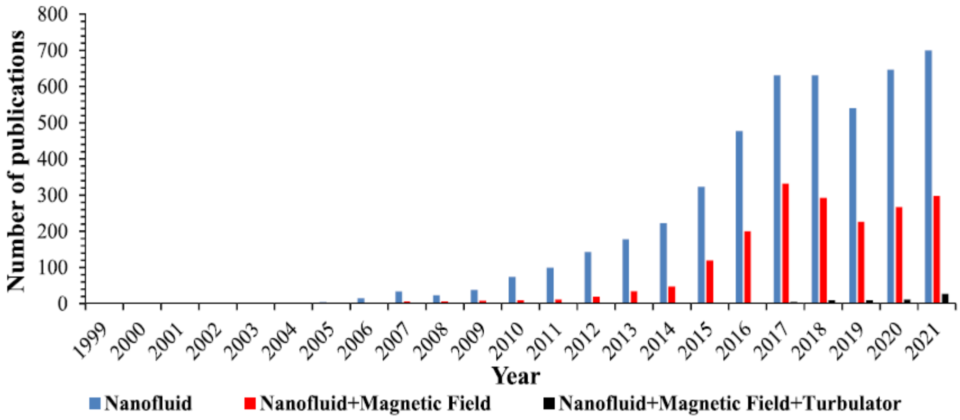

Fig. 2. Studies on internal forced convection including nanofluid, magnetic field and turbulator (data extracted from Scopus database as per paper submission)

The base fluid's thermal conductivity and heat transfer qualities can be enhanced by the addition of nanoparticles. It has been demonstrated that the flow and heat transmission in these hybrid nanofluids can be further improved by using magnetic fields. The effects of a magnetic field on the thermal conductivity and viscosity of a hybrid nanofluid made up of copper microparticles and iron oxide nanoparticles in water were examined in one study by Xu *et al.,* [21]. According to the findings, the magnetic field considerably improved the thermal conductivity and decreased the viscosity of the nanofluid, which enhanced heat transfer efficiency.

Another work by Sarafraz and Christo [22] studied the impact of a magnetic field on the flow and heat transfer properties of a water-based hybrid nanofluid made up of iron oxide and carbon nanotubes. The results revealed that the magnetic field considerably improved flow and heat transfer performance by raising the nanofluid's heat transfer coefficient and lowering its pressure drop.

Other methods have been employed in addition to magnetic fields to improve the flow and heat transfer characteristics of hybrid nanofluids. For instance, the base fluid's thermal conductivity and heat transfer capabilities have been increased by using ultrasonic waves to distribute and stabilise the nanoparticles is studied by Akbari *et al.,* [23]. Hybrid nanofluids' thermal conductivity and heat transfer qualities have also been improved using electromagnetic fields which employed by Kong and Lee [24].

Hybrid nanofluids have also been investigated for usage in several applications. Due to their enhanced thermal conductivity and heat transfer qualities, hybrid nanofluids, for instance, have been suggested as a viable coolant for nuclear reactors in the energy sector introduced by Wang *et al.,* [25]. Li *et al.,* [26] conducted a study investigating the potential utilisation of hybrid nanofluids as a heat transfer medium in spacecraft, owing to their advantageous characteristics such as low viscosity and high thermal conductivity. According to a study conducted by Irfan *et al.,* [27], researchers in the field of biomedical engineering have proposed the use of hybrid nanofluids in hyperthermia cancer treatment. This is attributed to the capability of these nanofluids to produce heat upon exposure to a magnetic field.

Even though these investigations produced some encouraging findings, more work needs to be done before hybrid nanofluids may be used in real-world applications. The stability of the nanoparticles in the base fluid is one difficulty. The flow and heat transfer characteristics of the nanofluid may be impacted because of the nanoparticles' propensity to aggregate and settle over time. Sanaei *et al.,* [28] examined a range of surface modification ways to stable the nanoparticles in the base fluid to solve this issue.

The present study aims to provide a comprehensive analysis of the inconsistent findings reported in multiple research projects on the enhancement of convective heat transfer using nanofluids, with an emphasis on hybrid nanofluids. In addition, this paper provides a brief description of the thermal properties and the convective heat transfer characteristics of the nanofluid. Subsequently, the convective heat transfer characteristics of the nanofluid are examined and analysed in relation to their increased outcomes. The main objective of this review is to examine the research findings relevant to the utilisation of a novel category of nanofluids in the presence of a magnetic field, as well as the improvements in convective heat transfer efficiency achieved via the use of various types of nanofluids. This investigation contains both experimental and numerical investigations. Hence, this study provides a comprehensive overview and comparative analysis of notable scholarly publications pertaining to the enhancement of convective heat transfer in nanofluids, encompassing hybrid nanofluids as well.

2. Materials and Methods

There have been several recent research on systematic assessments conducted across the world. However, in the context of an overview of employing hybrid nanofluid as a working fluid considering magnetic field effect, only a few studies were conducted recently. The following review will be divided into two parts: (1) hybrid nanofluid and (2) effect of a hybrid nanofluid and magnetic field on forced convective heat transfer. The next step in this section is a systematic evaluation and synthesis of the scientific literature to identify, select, and evaluate the importance of magnetic flow and heat transfer enhancement using hybrid nanofluid. Using hybrid nanofluids and applying a magnetic field are the two primary factors that significantly affect convective heat transfer and are discussed in this review considering recent findings. In this analysis, the pre-recording systematic reviews and meta-analysis (PRISMA) approach, a published guideline for conducting a systematic literature review, is used. Publication guidelines are usually necessary to direct writers in evaluating and reviewing a review's accuracy and rigor regarding pertinent and important details. The randomized studies assessments survey, which can be a significant factor in systematic analysis reports, are available for additional study forms was first introduced by Moher *et al.,* [29] in 2009 as shown in Figure 3.

As a result, the review aims to offer a glimpse into forthcoming research and act as a guide for researchers designing and examining more complex novel thermal energy applications, such as heat exchangers, heat pipes, thermosyphons, solar collectors, cooling electronics, flow control in channels, and hyperthermia in the medical field.

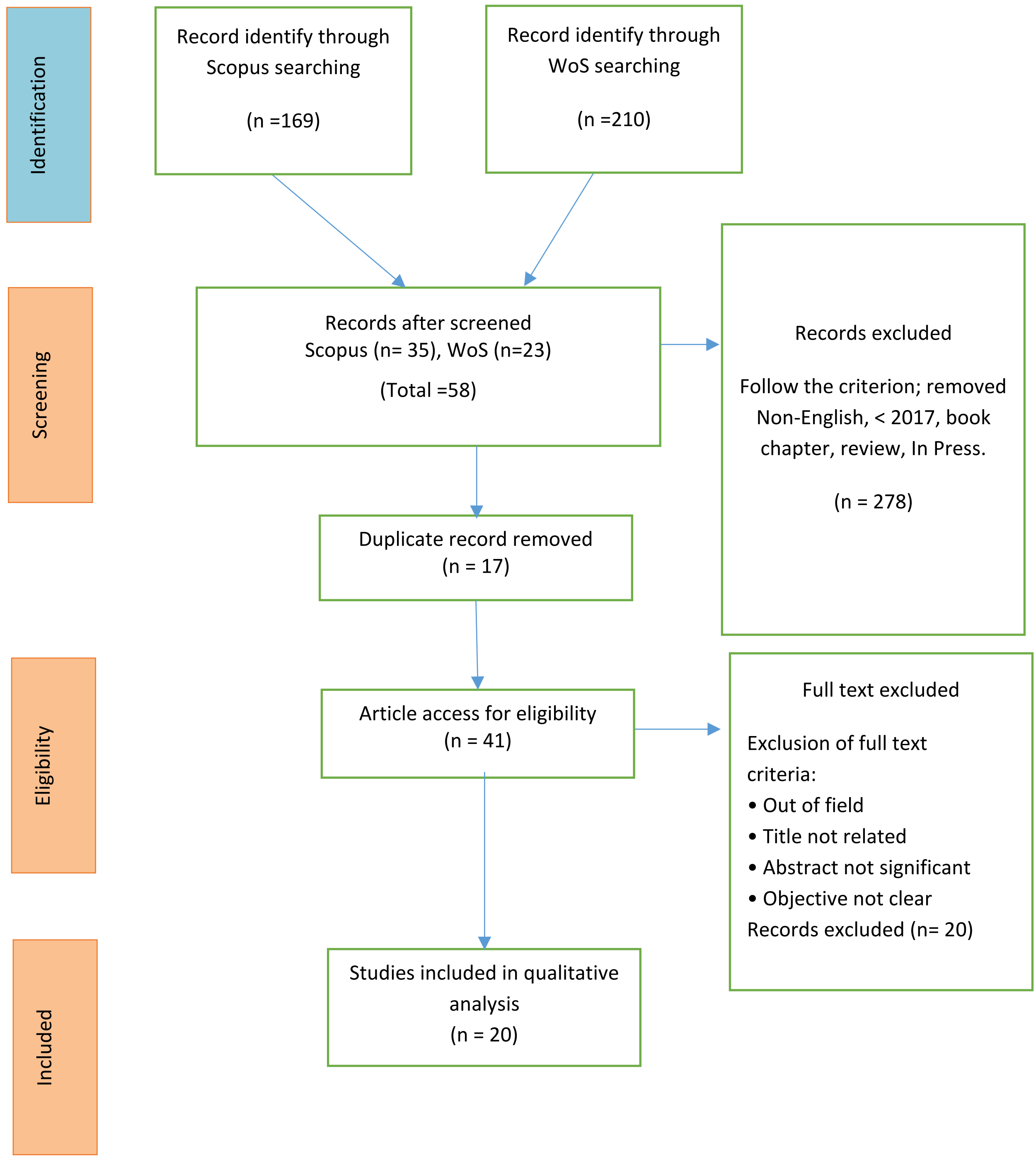

Fig. 3. Flow diagram of the proposed searching study [29]

2.1 Identification

The systematic review process consists of three basic phases that were used to choose many relevant papers for this study. The first phase entails the identification of keywords and the search for associated, related terms using thesaurus, dictionaries, encyclopaedias, and prior research. Following the selection of all pertinent keywords, search strings on Google Scholar and Eric as shown in Table 1 database have been created. The current study project was able to successfully obtain 379 papers from both databases during the first stage of the systematic review process.

Table 1
The search string

Scopus	TITLE-ABS-KEY (heat AND transfer AND magnetohydrodynamic "hybrid nanofluid") AND (LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "Malaysia") OR LIMIT-TO (AFFILCOUNTRY , "Romania")) Date of access: March 2023
WOS	Heat transfer AND magnetohydrodynamic "hybrid nanofluid" (Topic) and Ishak, Anuar or Pop (Authors) and 2022 or 2021 or 2020 or 2019 or 2018or 2017 (Publication Years) Analyze Results Citation Report Date of access: March 2023

2.2 Screening

Duplicated papers should be excluded during the first step of screening. The first phase omitted 17 articles, while the second phase screened 58 articles based on several inclusion-and- exclusion criteria developed by researchers. Literature (research articles) was the first criterion because it is the primary source of practical information. It also includes the exclusion from the current study of publications in the form systematic review, review, meta-analysis, meta-synthesis, book series, books, chapters, and conference proceedings. Furthermore, the review concentrated exclusively on papers written in English. It is essential to note that the schedule was chosen for a six-year duration (2017 – 2022). Otherwise, only studies carried out in hybrid nanofluid with magnetic effect have been selected to the analysis objective. In all, 278 publications based on specific parameters were excluded.

2.3 Eligibility

For the third step, known as eligibility, a total of 41 articles have been prepared. All articles' titles and key content were thoroughly reviewed at this stage to ensure that the inclusion requirements were fulfilled and fit into the present study with the current research aims. Therefore, two reports were omitted because they were not pure science articles based on empirical evidence. Finally, 21 articles are available for review as shown in Table 2.

Table 2
The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2017-2022	< 2017
Literature type	Journal (Article), Conference	Book, Review
Publication stage	Final	In press

2.4 Data Abstraction and Analysis

In this study, an integrative analysis was one of the examination techniques which was carried out to assess and synthesis several research designs qualitative, quantitative, and mixed methodologies. Expert research centered on developing appropriate topics and sub-topics. The first step in the development of the theme was the data collection phase. The authors have carefully reviewed a group of 20 papers for statements or information addressing questions from this current research. In the second step, the authors and experts analyze the heat transfer enhancement in hybrid nanofluid, determine and form meaningful groups. The two main themes that emerged from the approach are understanding, screening and challenges. The authors resumed each developed theme from here, including any themes, concepts, or ideas having any relationship. Within the framework of this study, the corresponding author worked with other co- authors to establish themes based on the findings. Here, a log was maintained during the data analysis process to document any analysis, opinions, puzzles, or other ideas relevant to the data interpretation.

3. Heat Transfer Characteristics of Hybrid Nanofluids

3.1 Experiments Studies on Convective Heat Transfer

Nanoparticles in hybrid nanofluids can significantly enhance the thermal conductivity of the base fluid, leading to improved heat transfer rates. Based on the searching technique, 20 articles were extracted and analyzed. All articles were categorized based on two main themes, which are hybrid nanofluid (10 articles) and magnetic field and the hybrid nanofluid (10 articles) as shown in Table 3.

Table 3
The research article finding based on the proposed searching criterion

Authors	Title	Year	Source title	Volume	Issue	Methodology
Kho *et al.,* [30]	Magnetohydrodynamics Ag-Fe_3O_4-Ethylene Glycol Hybrid Nanofluid Flow and Heat Transfer with Thermal Radiation	2022	CFD Letters	14	11	The hybrid nanofluid model's mathematical equations are created using the appropriate similarity transformations, and they are then numerically solved by running bvp4c codes in the Matlab software.
Soid *et al.,* [31]	Magnetohydrodynamic of Copper-Aluminium of Oxide Hybrid Nanoparticles Containing Gyrotactic Microorganisms over a Vertical Cylinder with Suction	2022	Journal of Advanced Research in Applied Sciences and Engineering Technology	28	2	The Tiwari-Das nanofluid model served as the foundation for the mathematical model's formulation. This study takes into account two different kinds of nanofluids that are submerged in water and contain copper (Cu) and aluminium oxide (Al_2O_3).
Pop *et al.,* [32]	MHD stagnation point flow on a shrinking surface with hybrid nanoparticles and melting phenomenon effects	2022	International Journal of Numerical Methods for Heat and Fluid Flow	32	5	The similarity equations are obtained using the similarity variables. The bvp4c solver is used to resolve these equations.
Wahid *et al.,* [33]	MHD hybrid nanofluid flow with convective heat transfer over a permeable	2022	International Journal of Numerical	32	5	The mathematical model is written as a set of partial differential

	stretching/shrinking surface with radiation		Methods for Heat and Fluid Flow			equations (PDEs), which are then changed using similarity variables into ordinary differential equations (ODEs).
Wahid *et al.,* [34]	MHD mixed convection flow of a hybrid nanofluid past a permeable vertical flat plate with thermal radiation effect	2022	Alexandria Engineering Journal	61	4	The governing flow and heat transfer equations are reduced to ordinary differential equations (ODEs) with the adoption of typical similarity transformations.
Waini *et al.,* [35]	Radiative and magnetohydrodynamic micropolar hybrid nanofluid flow over a shrinking sheet with Joule heating and viscous dissipation effects	2022	Neural Computing and Applications	34	5	The governing equations are transformed into similarity equations using the similarity variables. Then, to get the numerical results, MATLAB's bvp4c is applied.
Waini *et al.,* [36]	Stagnation point flow toward an exponentially shrinking sheet in a hybrid nanofluid	2022	International Journal of Numerical Methods for Heat and Fluid Flow	32	3	The boundary value problem solver, bvp4c, included in the MATLAB package, is used to numerically resolve the governing partial differential equations after they have been translated into a collection of similarity equations.
Roy *et al.,* [37]	Magnetohydrodynamic Natural Convective Hybrid Nanofluid Flow in a Square Enclosure with Different Blocks	2022	Iranian Journal of Science and Technology - Transactions of Mechanical Engineering			The velocity distribution, isotherm, local and average Nusselt numbers, as well as the variations in the Rayleigh number (Ra), Hartmann number (Ha), volume fraction of nanoparticles (ϕ), and radiation parameter (Rd), were used to analyse the fluid's flow and heat transfer behaviours.
Ibrahim *et al.,* [38]	Effect of MHD and Casson Free Convection Boundary Layer Flow Over a Stretching Sheet in Hybrid Nanofluid	2022	Lecture Notes in Mechanical Engineering			The boundary layer equations and dimensional governing equations are converted into partial differential equations (PDEs) by applying the appropriate similarity transformation and physical characteristics.
Waini *et al.,*	Flow over a shrinking	2022	Waves in Random and Complex			The partial differential

[39]	sheet containing hybrid nanoparticles with nonlinear thermal radiation and magnetohydrodynamic effects		Media			equations are transformed into similarity equations of a specific form by using relevant similarity variables.
Waini *et al.,* [40]	Magnetohydrodynamic flow past a shrinking vertical sheet in a dusty hybrid nanofluid with thermal radiation	2022	Applied Mathematics and Mechanics (English Edition)	43	1	The outcome shows that the shrinking scenario can have a number of different outcomes. The rate of heat transmission and the friction factor both increase when the magnetic parameter and the volume percentage of copper nanoparticles increase.
Yashkun *et al.,* [41]	MHD hybrid nanofluid flow over a permeable stretching/shrinking sheet with thermal radiation effect	2021	International Journal of Numerical Methods for Heat and Fluid Flow	31	3	Using similarity transformation, mathematical equations are converted into pairs of self-similarity equations. It was decided to use MATLAB's Boundary Value Problem Solver (bvp4c) to solve the system of reduced similarity equations.
Zainal *et al.,* [42]	Stability analysis of MHD hybrid nanofluid flow over a stretching/ shrinking sheet with quadratic velocity	2021	Alexandria Engineering Journal	60	1	The governing equations are converted to the similarity equations and then solved numerically in the Matlab bvp4c program by varying several controlling parameters.
Yahaya *et al.,* [43]	Magnetohydrodynamic Flow of Hybrid Ag-Cuo/H_2O Nanofluid Past a Stretching/Shrinking Porous Plate with Viscous-Ohmic Dissipation and Heat Generation/ Absorption	2021	Magnetohydrodynamics	57	3	The concept of hybridising various nanoparticles stems from the search for working fluids with superior hydrodynamic and thermophysical properties for applications involving heat transfer.
Lund *et al.,* [44]	Magnetohydrodynamic flow of Cu–Fe_3O_4/H_2O hybrid nanofluid with effect of viscous dissipation: dual similarity solutions	2021	Journal of Thermal Analysis and Calorimetry	143	2	The system of ordinary differential equations (ODEs) is obtained by applying similarity transformations on the model of partial differential equations.
Jamaludin *et al.,* [45]	MHD mixed convection stagnation-point flow of	2020	European Journal of	84		This research concentrated on the Cu-

	$Cu-Al_2O_3$/water hybrid nanofluid over a permeable stretching/shrinking surface with heat source/sink		Mechanics, B/Fluids			Al_2O_3/water hybrid nanofluid to address the problem of mixed convection stagnation-point flow and heat transmission over a permeable stretching/shrinking sheet with the magnetic field and heat source/sink effects.
Aly and Pop [46]	MHD flow and heat transfer near stagnation point over a stretching/shrinking surface with partial slip and viscous dissipation: Hybrid nanofluid versus nanofluid	2020	Powder Technology	367		A hybrid nanofluid with partial slip and viscous dissipation was theoretically and statistically investigated for its steady magnetohydrodynamic stagnation point flow and heat transfer over a stretching/shrinking surface.
Lund *et al.,* [47]	Dual solutions and stability analysis of a hybrid nanofluid over a stretching/shrinking sheet executing MHD flow	2020	Symmetry	12	2	In this paper, the unsteady magnetohydrodynamic (MHD) flow of hybrid nanofluid (HNF) composed of Cu-Al_2O_3/water in the presence of a thermal radiation effect over the stretching/shrinking sheet is investigated.
Wahid *et al.,* [48]	Mhd hybrid cu-Al_2O_3/water nanofluid flow with thermal radiation and partial slip past a permeable stretching surface: analytical solution	2020	Journal of Nano Research	64		This work describes the impact of thermal radiation effects and velocity slip on the magnetohydrodynamic hybrid Cu-Al_2O_3/water nanofluid flow over a permeable stretched sheet.
Anuar *et al.,* [49]	Cu-Al_2O_3/Water Hybrid Nanofluid Stagnation Point Flow Past MHD Stretching/Shrinking Sheet in Presence of Homogeneous-Heterogeneous and Convective Boundary Conditions	2020	MDPI Journal	8	8	The partial differential equations (PDEs) were changed into a system of ordinary (similarity) differential equations (ODEs) by adding a correct similarity variable then solved numerically using Matlab software.

3.2 Which Hybrid Nanofluids?

A class of nanofluids known as hybrid nanofluids combines various kinds of nanoparticles with a base fluid. They are used to generate beneficial effects or to improve certain characteristics. It is advantageous in thermal systems because it positively enhances convective heat transmission, and there are lots of experimental investigations on its characteristics and uses. Figure 4 illustrates a few of these potential real-world uses.

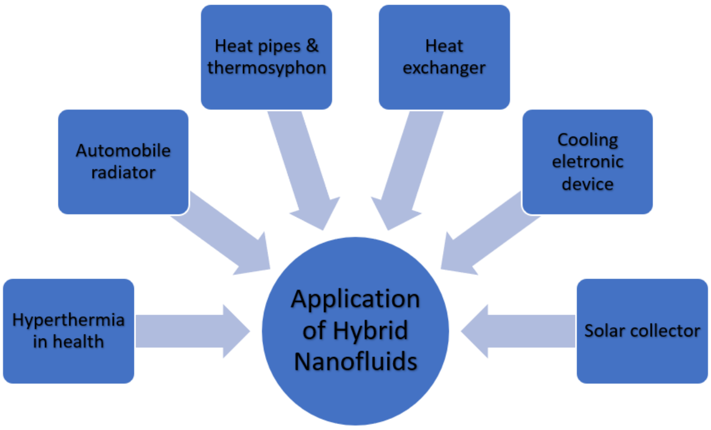

Fig. 4. Several possible applications of hybrid nanofluids

According to a report, the use of hybrid nanotechnology in numerous industries (materials, equipment, and gadgets) has grown significantly in recent years. Although hybrid nanofluids have many benefits for heat transmission, they also have significant downsides as shown in Figure 5. In this article it is easy to see that the primary problems with nanofluids are their tendency to aggregate and their high cost for nanoparticles. Despite this, hybrid nanofluids are one of the most researched topics in the present literature due to their better heat transfer capabilities and significant research opportunities.

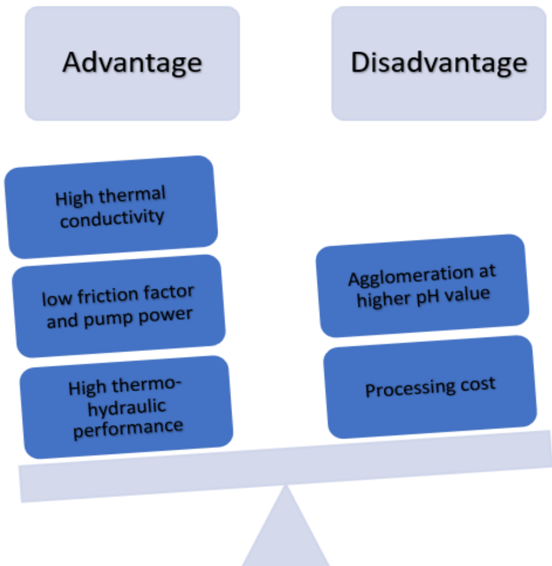

Fig. 5. Some advantages and disadvantages of hybrid nanofluids

Most previous investigations have shown that Al_2O_3/water and CuO/water nanofluids have an improved convectional heat transfer coefficient, which increases dramatically as the nanoparticle and Re concentrations increase. Experiment results revealed that the maximum improvement with an Al_2O_3/water nanofluid was approximately 52%, whereas the maximum improvement with CuO/water was roughly 60. This is mostly due to the CuO nanoparticles' greater thermal conductivity and low specific heat was investigated by Mojarrad *et al.,* [50]. Figure 6 shows the ratio of a nanofluid's convective heat transfer coefficient to that of the base fluid at various Re values. Despite several recent developments reporting an increase in convective heat transfer in a nanofluid, more experiment results and detailed mechanisms of nanoparticle movements in a nanofluid are still needed for a better understanding of heat transfer and fluid flow behaviour in a nanofluid.

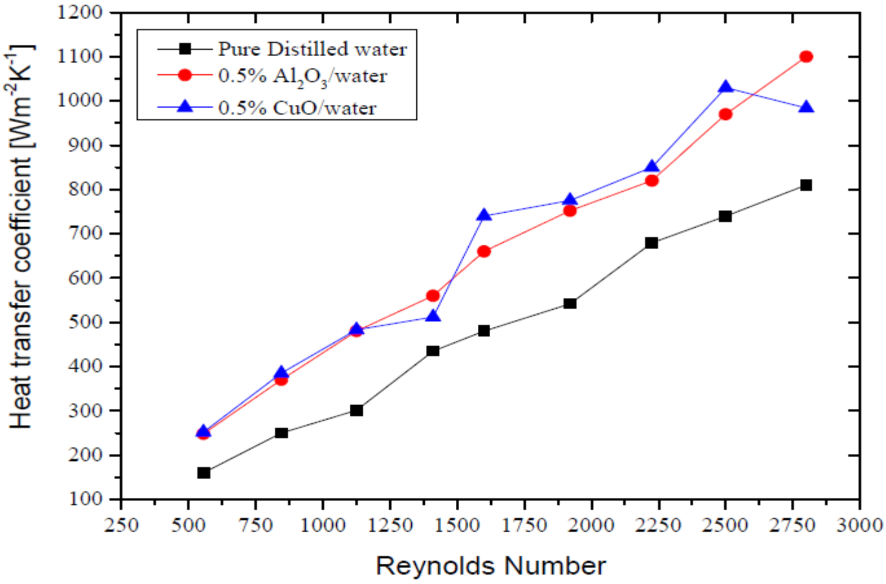

Fig. 6. Comparison of convective heat transfer coefficient according to Re of distilled water and 0.5 vol% loading of Al_2O_3 and CuO nanopowder water [50]

Magnetic flow and convective heat transfer can be enhanced by combining metallic and magnetic nanoparticles examined by Kho *et al.,* [30]. Iron oxide, nickel ferrite, and nickel ferrite are some types of magnetic nanoparticles that can be mixed. These hybrid nanofluids have shown promise in a range of applications, such as cooling systems, heat exchangers, and electrical devices.

In a different study, Soid *et al.,* [31] investigated the effects of hybrid nanofluids, comprising copper-aluminum oxide hybrid nanoparticles with gyrotactic microorganisms, over a stretching vertical cylinder with suction. The inclusion of both types of nanoparticles increased the thermal conductivity and heat transfer coefficients of hybrid nanofluid in comparison to base fluid, making it faster in terms of transit rate than nanofluid.

Another work by Pop *et al.,* [32] investigated the impact of hybrid nanofluids including magnetic copper (Cu) nanoparticles and aluminium oxide (Al_2O_3) nanoparticles on convective heat transfer. In comparison to the base fluid devoid of magnetic nanoparticles, the researchers found that applying a magnetic field perpendicular to the fluid flow resulted in faster heat transfer rates.

Wahid *et al.,* [33] numerically analyzed metal oxide-metal hybrid nanofluids revealed that these nanofluids mix metal nanoparticles dispersed in a base fluid with metal oxide nanoparticles (such as alumina, titania, or zinc oxide). While metal oxide nanoparticles offer stability and avoid agglomeration, metal nanoparticles improve heat conductivity.

Experimental research on carbon nanotube-metal oxide hybrid nanofluids was conducted by Wahid *et al.,* [34]. Hybrid nanofluids are made up of carbon nanotubes (CNTs) and metal oxide nanoparticles. Excellent thermal conductivity is a characteristic of CNTs, and metal oxide nanoparticles enhance CNTs' stability during dispersion in the base fluid. The CNTs enhance the dispersion and stability of the metal nanoparticles while adding additional heat transfer channels.

Combining magnetic nanoparticles, such as iron oxide (Fe_3O_4) or nickel ferrite ($NiFe_2O_4$), with metallic nanoparticles, such as copper (Cu) or silver (Ag), can result in enhanced convective heat transfer and magnetic flow effects, according to Waini *et al.,* [35,36] numerical investigation of this topic. These hybrid nanofluids have demonstrated potential in a variety of applications, including electronic devices, heat exchangers, and cooling systems.

Roy *et al.,* [37] investigated magnetic nanoparticles made of carbon. In their study, the combined impact on heat transfer and magnetic flow of hybrid nanofluids including magnetic nanoparticles and carbon-based nanoparticles, such as carbon nanotubes (CNTs) or graphene, have been studied. Improved heat transfer performance is a result of the special qualities of carbon-based nanoparticles combined with the magnetic response of magnetic nanoparticles.

Ibrahim *et al.,* [38] numerically investigated the combining magnetic nanoparticles with metal oxide nanoparticles, including zinc oxide (ZnO), alumina (Al_2O_3), or titania (TiO_2), can result in hybrid nanofluids with improved thermal conductivity and magnetohydrodynamic characteristics. These nanofluids have been investigated for a variety of uses, including improving heat transfer and tinkering with magnetic fields.

The combined impacts of several metallic nanoparticles, such as copper, aluminium, and silver, in a single hybrid nanofluid was explored by Waini *et al.,* [39,40] in their study on hybrid nanofluids with many types of metallic nanoparticles. These hybrid nanoparticles can work synergistically to increase magnetic flow behaviour and convective heat transfer. This action enables the applied external magnetic field to regulate the flow and heat transfer processes.

The effects of utilizing titania TiO_2/water and alumina Al_2O_3/water nanofluids as working fluids in an annular channel was experimentally examined by Yashkun *et al.,* [41]. It was found that the volume fraction of nanoparticles directly correlates with the convective heat transfer increase. Researchers continue to examine and optimize various combinations of nanoparticles and base fluids to achieve the most effective improvement of magnetic flow and convective heat transfer. Overall, studies on hybrid nanofluids have produced results that are encouraging for improving heat transfer efficiency. It is important to note that additional research is still needed to analyse these fluids' long-term dependability and potential environmental effects as well as to optimize the nanoparticle combinations, concentrations, and stability of these systems.

3.3 Experiment Studies on Convective Heat Transfer of Magnetic Hybrid Nanofluids Under Magnetic Field

Hartmann was the first to investigate the behavior of fluids in a magnetic field and the results of his research have influenced many other scientists and served as a template for a wide range of experimental and numerical studies. The previous research also conclusively shows how the viscosity, flow rate, and pressure drop of fluids in a particular channel can alter under the effect of an applied external magnetic field. According to research that is currently accessible, an external magnetic field has been discovered to increase the viscosity and pressure values of the flow while lowering the flow speeds. Additionally, pertinent findings demonstrate that the magnetic field effect has a greater impact on fluids with higher densities examined by Zainal *et al.,* [42]. Newtonian and non-Newtonian fluids, including liquid metal alloys, Dilatant fluid, Bingham fluid, Oldroyd-B fluid, viscoelastic fluid, Sisko fluid, power-law fluid, magnetorheological fluid, ferrofluid, and magnetic nanofluid, are frequently used in channels flowing under the influence of magnetic fields as shown in Figure 7.

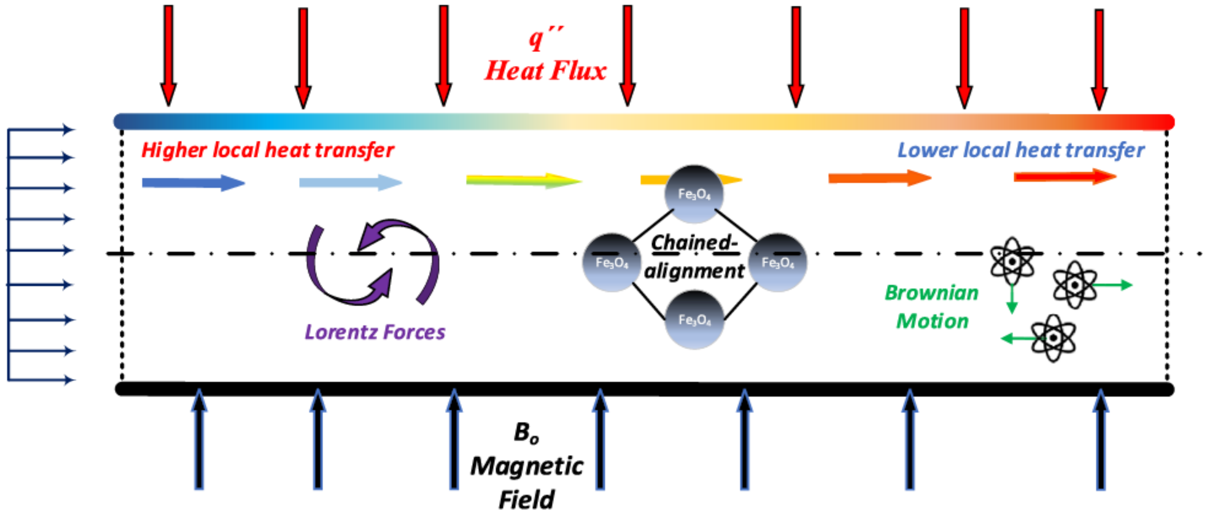

Fig. 7. The phenomenon of magnetic field and hybrid nanofluid in a channel [42]

These fluids are used in a variety of processes, such as membrane systems, geothermal operations, power generators, nuclear reactors, water treatment, cooling systems, pumps, magneto-rheological brakes, biomedical applications, hydrofoil lift systems, vibration isolators, metallurgical processing, aviation, and space technologies, as researched by Yahaya and Arifin [43]. Only a handful of the outcomes will be described in the lines that follow, even though countless researchers have had a significant impact on the state of the art in this field. Lund *et al.*, [44] conducted an analytical investigation of the two-dimensional convective heat transfer behaviour of an axially symmetric incompressible viscous fluid flow in a circular pipe using the Homotopy Analysis Method (HAM). Constant wall temperature has been used as a boundary condition. The flow was pushed into the channel by applying external uniform suction in opposing and axial directions on the channel wall and keeping a constant magnetic field. Jamaludin *et al.,* [45] examined the heat transfer and MHD flow characteristics of micropolar and Newtonian fluids travelling immiscibly via a circular conduit under steady-state circumstances. It is anticipated that the pipe will be filled with a uniform porous media. Numerical solutions for temperature, microrotation, and velocity were obtained using the finite difference approach. When an external magnetic field is applied, the fluid flow patterns are changed, improving the efficiency of heat transfer and its coefficients. This improvement is especially important in systems with fluids with high thermal conductivity. After evaluating the review papers mentioned above, it can be said that the magnetizable and non-magnetizable characteristics of the nanofluids are crucial factors that influence the flow and heat transfer behaviour under the magnetic field. Fe, Co, Ni, and Gd elements as well as oxide compounds are more sensitive to the magnetic field than metal, metal oxide, and carbon-based nanoparticles with weak magnetic permeability because the relative magnetic permeability is above 1 studied by Aly and Pop [46]. Using base fluids like water, oil, ethylene glycol, etc., magnetic nanofluids—a new class of heat transfer fluids—can be created by distributing superparamagnetic nanoparticles with a typical diameter of less than 20 nm. Metallic elements including iron, nickel, and cobalt, as well as their oxides like magnetite (Fe_3O_4), are among the nanoparticles employed in these nanofluids. The applied magnetic field can influence the thermophysical characteristics of magnetic nanofluids based on several factors, including the kind and proportion of nanoparticles as well as the direction, strength, and orientation of the magnetic field. This phenomenon enables the external magnetic field to be used to control the flow and heat transfer processes was examined by Lund *et al.,* [47].

The Brownian motion of the nanoparticle chains and the disruption of the boundary layer between the channel wall and the fluid enhance the heat transfer rate. With the magnetic field effect being applied to the nanofluid moving in the channel, the nanoparticles are exposed to Kelvin forces was studied by Wahid *et al.,* [48]. Rotating flows result from this, with the channel's wall receiving the primary flow. As a result, the thermal boundary layer is disturbed, increasing heat convection. On the other hand, the application of a magnetic field in nanofluid flows appears to be an essential factor influencing convective heat transfer, as demonstrated by the studies described previously. This suggests that in such flows, the magnetic field can regulate the flow and heat transfer. The main effects of the magnetic field are an increase in convective heat transmission and a chain-like structure in the flow. Contrary to the earlier findings, Anuar *et al.,* [49] explored MHD flow and mixed convective heat transfer of Cu-Al_2O_3/water hybrid nanofluid inside a vertical microchannel in the presence of the Lorentz force. The results of the experiment showed that, particularly for the lower nanoparticle volume fractions, the Nusselt number can be raised in the presence of the magnetic field.

Uysal *et al.,* [51] studied the laminar forced convection heat transfer and entropy production rate of a diamond-Fe_3O_4 water-based hybrid nanofluid in a rectangular mini-channel numerically. Based on a modest temperature differential between the wall temperature and the bulk temperature of the hybrid nanofluid, the diamond-Fe_3O_4/water hybrid nanofluid demonstrated the highest convective heat transfer coefficient. A diamond-Fe_3O_4/water hybrid nanofluid also had the highest flow velocity. Figure 8 compares the convective heat transfer rate of a diamond-Fe_3O_4/water hybrid nanofluid to a standard nanofluid at 0.2 vol% nanoparticle concentration. In general, hybrid nanofluids outperform single nanofluids in terms of enhancing the convective heat transfer coefficient. Most of the numerical results showed that as the Re and nanoparticle concentrations increased, so did the convective heat transfer coefficient. The increased concentration in a hybrid nanofluid exhibits thinning shear behaviour of a non-Newtonian fluid, which is highly significant in terms of improving convective heat transfer, particularly in the entrance length area.

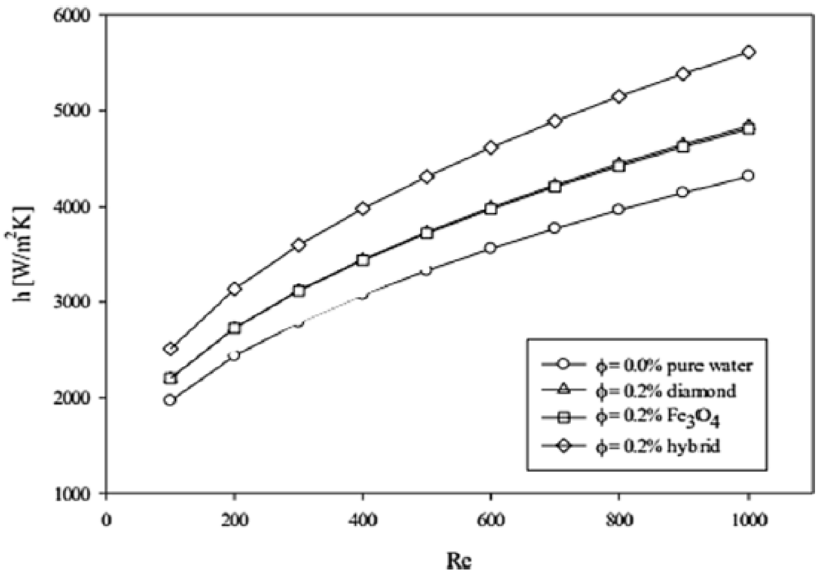

Fig. 8. Numerical investigations into convective heat transfer coefficient for conventional and hybrid nanofluids [51]

The improvement in convective heat transfer characteristics rises with increasing nanofluid concentration as the thermal conductivity of the base fluid decreases. Furthermore, it increases as the magnetic field strength increases. Despite thorough studies on nanofluid preparation and convective heat transfer measurements, a firm knowledge of the convective heat transfer mechanism in various nanofluids has yet to be achieved. As a result, more study on the convective heat transfer of nanofluids is still needed, and a precise theory on the flow mechanism of diverse fluids has yet to be established.

4. Recent Developments and Future Perspective

There are few experimental and numerical investigations on the combined impact of applying a magnetic field, utilizing nanofluid as the working fluid and positioning turbulators in a channel on convective heat transfer rate in the literature. Even though these studies have a high level of applicability, more experimental work is strongly advised to detail all the advantages and disadvantages of combining these heat transfer augmentation approaches. For further research, some recent developments that can be summed up as follows

i. Multi-Objective Optimization: Future research could focus on multi-objective optimization techniques to simultaneously enhance heat transfer performance while considering other factors such as pressure drop, cost, and environmental impact. Such optimization studies could help identify optimal combinations of magnetic field strength, nanoparticle concentration, and fluid flow conditions that achieve both efficient heat transfer enhancement and practical feasibility.
ii. Advanced Characterization Techniques: Continued advancements in characterization techniques will contribute to a deeper understanding of the behaviour and properties of hybrid nanofluids under the influence of magnetic flow. Techniques such as electron microscopy, spectroscopy, and X-ray diffraction can provide detailed insights into the dispersion, aggregation, and structural changes of nanoparticles in nanofluids, aiding in the development of more efficient and stable formulations.
iii. Expansion and Practical Applications: Further research is needed to address the challenges of scale-up and implementation of magnetic flow and hybrid nanofluid systems in real-world applications. Scaling up the technology while maintaining the desired heat transfer enhancement, stability, and cost-effectiveness is crucial for practical adoption in industrial and commercial settings.
iv. Novel Methods for Generating Magnetic Fields: Exploring novel methods for generating magnetic fields, such as electromagnetic systems or magnetic nanoparticles, could offer new possibilities for controlling fluid flow and heat transfer. These innovative approaches may provide enhanced performance, improved system flexibility, and better integration with existing heat transfer systems.
v. Multiple Physical Coupling: Investigating the coupling of magnetic flow and convective heat transfer with other physical phenomena, such as fluid-solid interactions or phase change processes, can open new avenues for research. Understanding the interplay between magnetic fields, heat transfer, and other physical phenomena will enable the development of advanced systems for specific applications, such as thermal management in electronics or energy conversion devices.

5. Conclusions

In conclusion, the effect of magnetic flow and convective heat transfer enhancement using hybrid nanofluids has shown promising results and potential for improving heat transfer performance. The combination of magnetic flow and hybrid nanofluids has been found to increase heat transfer coefficients, improve fluid mixing, and enhance thermal conductivity, resulting in enhanced convective heat transfer rates.

Recent developments in the field have focused on advanced nanoparticle synthesis, surface modification techniques, optimization of hybrid nanofluid formulations, and numerical simulations to further understand and optimize the heat transfer enhancement process. These advancements contribute to the ongoing research and development of efficient heat transfer technologies.

Future perspectives include multi-objective optimization, advanced characterization techniques, scale-up and practical application considerations, novel magnetic field generation techniques, and exploring multi-physics coupling. These areas of focus aim to address challenges, improve system performance, and expand the practical implementation of magnetic flow and hybrid nanofluid systems in various industries.

Overall, the research on the effect of magnetic flow and convective heat transfer enhancement using hybrid nanofluids demonstrates the potential for significant improvements in heat transfer performance. Further research and innovation in this field are expected to contribute to the development of efficient heat transfer systems with applications in areas such as thermal management, energy conversion, and industrial processes. As a general conclusion, a combination of different heat transfer enhancement techniques can be of certain advantage in attaining high heat transfer rates. However, it is clear from the state of the art that a lot of work is still ongoing, and a lot of hypotheses are under evaluation. Nevertheless, it is clear from the state of the art that applying external magnetic field to hybrid nanofluids flow has great potential to attain high heat transfer rates.

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